UCRL-JC-124239
PREPRINT

Diagnostics for High Density Implosions at the National Ignition Facility

M.D. Cable
T.W. Barbee
R.A. Lerche
M.B. Nelson
M.J. Moran
D.B. Ress
T.C. Sangster
J.E. Trebes
R.E. Turner
T.W. Phillips
Lawrence Livermore National Laboratory

D. Hicks
C.K. Li
R.D. Petrasso
F. Seguin
Plasma Fusion Center, Massachusetts Institute of Technology

**This paper was prepared for submittal to the
16th International Atomic Energy Agency Fusion Energy Conference
Montreal, Canada, 7–11 October 1996**

October 1996

DIAGNOSTICS FOR HIGH DENSITY IMPLOSIONS AT THE NATIONAL IGNITION FACILITY

M.D. Cable[1], T.W. Barbee, R.A. Lerche, M.B. Nelson, M.J. Moran, D.B. Ress, T.C. Sangster, J.E. Trebes, R.E. Turner, and T.W. Phillips

University of California, Lawrence Livermore National Laboratory,
P. O. Box 808, Livermore, California 94551, USA

[1]Current address: University of Rochester, Laboratory for Laser Energetics,
250 East River Road, Rochester, New York 14623, USA

D. Hicks, C.K. Li, R.D. Petrasso, and F. Seguin

Plasma Fusion Center, NW17-256, Massachusetts Institute of Technology,
Cambridge, Massachusetts 02138, USA

1. Abstract

The proposed National Ignition Facility (NIF) is a large (1.8 MJ on target at 0.35 μm) multi-beam laser facility that will be used for Inertial Confinement Fusion (ICF). ICF implosions at this facility will produce core plasma temperatures over 10 keV and densities over 100 g/cm^3. Properties of these plasmas can be measured by a variety of optical, x-ray, and nuclear diagnostic techniques such as those used at existing facilities like the Nova laser at the Lawrence Livermore National Laboratory (LLNL). Some of these currently used techniques will be directly applicable to NIF; others require significant development. Damage of components close to the target will be a much greater issue at NIF, necessitating the development of distant detector techniques. X-ray-based core diagnostics will need to utilize substantially higher energies than are in routine use today. Penetrating nuclear-particle-based diagnostics will be particularly well suited to these implosions, and the higher nuclear yields will allow new techniques to be developed. A summary of diagnostics used for high-density-implosion experiments at Nova and development of new techniques for NIF are discussed.

2. Introduction

The National Ignition Facility (NIF) will deliver ~1.8 MJ of 0.35-μm light onto mm-scale hohlraum targets with the expectation of controlled thermonuclear ignition and gain (20-MJ yield). Ignition targets will achieve core plasma temperatures in excess of 10 keV and densities of order 100 g/cm^3. Under these conditions, the expected fusion yields of up to 10^{19} neutrons will far surpass the record neutron yields achieved at Nova (4×10^{13}) and, more recently, at the Omega Laser Facility at the University of Rochester (10^{14}). Before the first ignition experiments can occur, however, a comprehensive set of diagnostic measurements will be required to characterize the performance of both the laser and the hohlraum targets. Many of these diagnostics have counterparts at laser facilities such as Nova; however, some will require the development of new techniques and instrumentation.

The diagnostics required to validate NIF hohlraum targets fall into two distinct categories: (1) those used to measure the hohlraum temperature and radiation drive spatial symmetry, and (2) those used to characterize the performance of the imploding capsule. The first category of diagnostics will utilize x-ray imaging systems and shock break-out measurements; the second category will rely heavily on nuclear reaction products and very high energy x-ray-based techniques. The implosion diagnostics are discussed below.

3. Fuel Areal Density

The compressed fuel areal density ($\langle\rho R\rangle$) at burn time is a critical parameter for an ICF implosion. In order for a capsule to ignite and burn, a $\langle\rho R\rangle$ of 1–2 g/cm^2 is required. At Nova, $\langle\rho R\rangle$ is determined by measurements of secondary neutrons[1,2,3] produced in the following two-step reaction sequence in initially pure deuterium fuel.

1) $d + d \longrightarrow p + t$ (1.01 MeV t)
2) $t + d \longrightarrow \alpha + n$ (11.8–17.1 MeV n)

Since the probability that the energetic triton produced in reaction 1 produces a "secondary" neutron in reaction 2 is a function of the fuel $\langle\rho R\rangle$ through which the triton passes, a measurement of the number of secondary neutrons and a determination of their energy spectrum can be used to determine areal density.

However, the 1.01-MeV triton range must be greater than the fuel <ρR> to be determined, limiting this technique to values less than about 0.1 g/cm^2.

For larger targets with higher yields, a similar measurement can be made of "tertiary" neutrons produced in the following three-step reaction sequence in a mixed deuterium and tritium fuel.

3)	$d + t \longrightarrow \alpha + n$	(14.05 MeV n)
4)	$n + d \longrightarrow n' + d'$	(0–12.5 MeV d)
5)	$d' + t \longrightarrow \alpha + n$	(12–30 MeV n)

Note that high-energy tertiary neutrons are also produced if reaction 4 (elastic scattering) occurs between a neutron and a fuel triton or even between the alpha particle produced in reaction 3 and a fuel deuteron or triton. However, the sequence shown results in the highest reaction product energies. Figure 1 shows the neutron energy spectrum produced from all reactions for a Nova-scale implosion.

The probabilities of both reactions 4 and 5 occurring are dependent upon the fuel <ρR> through which the energetic particle initiating the reaction passes. Thus, as for the secondary neutron case, a measurement of tertiary neutrons can provide a determination of fuel areal density. In this case, however, the energies of the charged particles (and, correspondingly, their ranges) are much higher. Tertiary neutron measurements can be used to determine fuel areal densities up to several g/cm^2. At Nova, secondary neutron measurements are made with an array of neutron time-of-flight detectors[4]; the yields and areal densities are too low to allow detection of tertiary neutrons. However, at NIF, even pre-ignition experiments will result in high enough yields and areal densities that a similar instrument will allow measurements of tertiary neutrons.

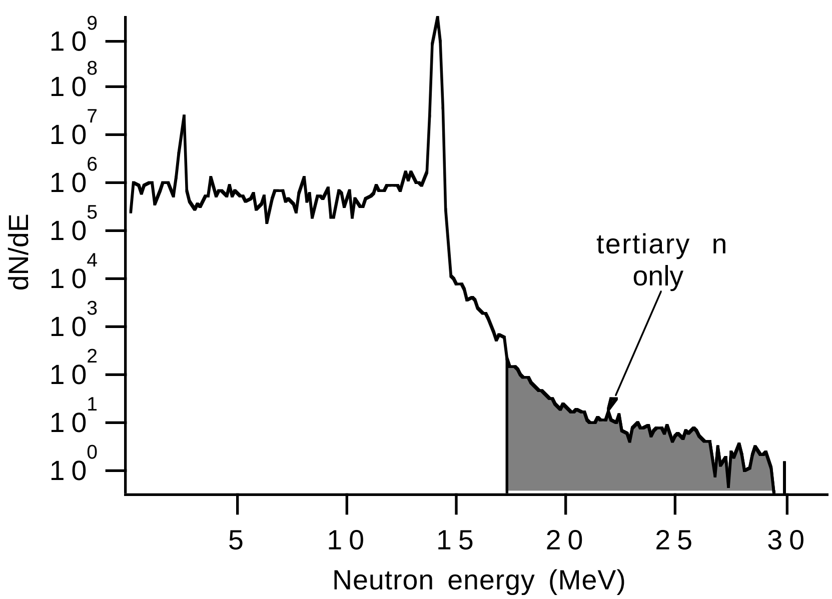

Fig. 1. Neutron energy spectrum for a deuterium- and tritium-filled Nova target. Region containing only neutrons from the tertiary sequence of reactions is shaded.

4. Nuclear Reaction History

Nuclear reaction rate measured as a function of time (nuclear reaction history) is an important quantity to determine the dynamics of the implosion process. At Nova, nuclear reactions proceed at a measurable rate for the 100–200 ps of the implosion. Neutron yield is measured as a function of time with <30 ps-resolution, using a neutron-sensitive, plastic scintillator located a few centimeters from the target[5]. Light from this scintillator is imaged to a streak camera located outside the target chamber. The fast rise time of the scintillator (<20 ps) allows a deconvolution of the observed signal that results in a measurement of the reaction history. Figure 2 shows data obtained from a typical Nova target[6].

The scintillator is located close to the target in order to avoid the time dispersion associated with the spread in neutron velocities due to the broadening of the energy spectrum for neutrons produced in a high temperature plasma (see below). For NIF, the high energy of the laser and the even higher energies of high-gain targets will preclude locating diagnostic components this close to the target. Therefore, a system based on measurement of the 16.7-MeV γ-rays produced in the $^3H(d,\gamma)^5He$ reaction is being developed. These γ-rays are produced in much smaller numbers (branching ratio approximately 5×10^{-5}) than the primary neutrons from the $^3H(d,n)^4He$ reaction, so a sensitive, background resistant technique is required.

One such approach currently under development at LLNL is to replace the scintillator with an aerogel foam that serves as a low-density Cherenkov radiator. Incident high-energy γ-rays react in a surrounding Hevimet shield to produce high-energy positrons and electrons, which travel into the foam and produce Cherenkov light if they are above the several-MeV threshold determined by the index of refraction of the aerogel used. This system can be made very insensitive to lower-energy photons and has been used successfully to observe high-energy γ-rays at Nova. In order to increase system sensitivity and thus allow operation with the detector several meters from a NIF target, high-efficiency Cherenkov radiator designs are also being developed. Figure 3 shows a diagram of a specially shaped Lucite radiator designed so that the cone angle matches the conical angle of emission of the Cherenkov light, thus allowing efficient collection and focusing from a large solid angle[7].

5. Fuel Ion Temperature

Another important parameter of an ICF implosion is the fuel ion temperature. Nuclear reactions between the fuel ions produce products with energy spectra that are dependent upon the ion temperature (Doppler broadening)[8]. In particular, neutron time-of-flight spectroscopy has been used to measure the energy spectra of the 2.45-MeV neutrons from the $D(d,n)^3He$ reaction, and of the 14.05-MeV neutrons from the $^3H(d,n)^4He$ reaction[9]. For the relatively low yields and temperatures of present facilities, such as Nova, it has been necessary to use sensitive, high-resolution spectrometers based on arrays of time-of-flight detectors similar to those used for the secondary neutron measurements described above[10]. For the higher yields and temperatures of NIF, simpler current mode detectors will suffice to measure the burn-averaged fuel ion temperature. For this measurement, maintaining clear, well collimated flight paths around the crowded target area is likely to be the major consideration for obtaining good measurements.

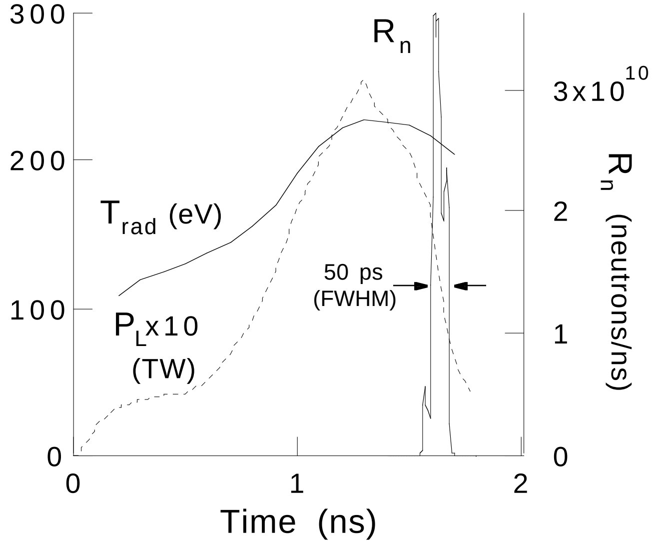

Fig. 2. Nuclear reaction history measured at Nova with the neutron-based technique shown relative to the laser power (P_L) and the hohlraum radiation temperature (T_{rad}).

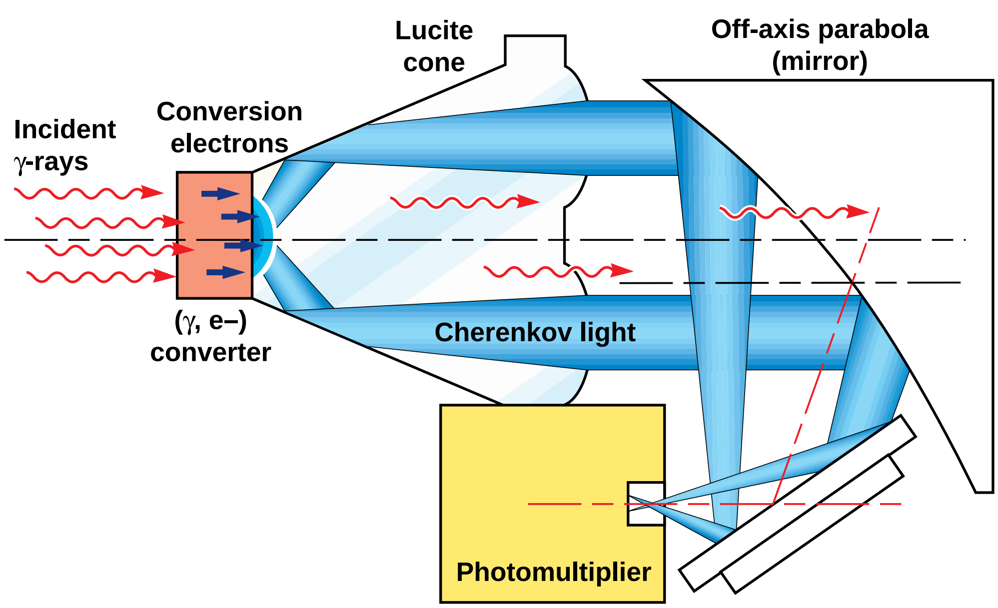

Fig. 3. High efficiency Cherenkov radiator. High-energy γ rays scatter high-energy electrons into the Lucite Cherenkov cone, which is designed to reflect and focus light onto a detector at the focal plane.

However, higher yields and temperatures not only simplify measurements of burn-averaged temperature, but additionally open the possibility of time-resolved ion temperature measurements. Nuclear reactions at NIF will occur over a period of several hundred picoseconds in the final stages of the implosion (see the discussion of reaction history above), thus making it possible to observe the evolution of the fuel temperature during this time. There are two possibilities under consideration. The first is a neutron time-of-flight-based measurement. However, as in the measurements of nuclear reaction histories, the broadened energy spectrum of neutrons produced from a high-temperature target results in time dispersion at the end of the flight path. This necessitates a simultaneous determination of both the arrival time and the energy of each neutron. Such a measurement can possibly be achieved via, for example, an array of proton recoil detectors, however the high resolution required for both the time (<50 ps) and energy (<20 keV) measurements make it challenging. A second approach, which may turn out to be simpler, is to use a γ-ray-based system to circumvent the time dispersion problem, as is being done for reaction history measurements. Here, the ion temperature measurement would be made using a direct energy measurement of the Doppler-broadened γ-ray spectrum from an appropriate nuclear reaction. Time resolution could be achieved by a gating technique. Technology development appropriate for both approaches is currently underway.

6. Imaging

Implosion symmetry for ICF has been typically measured with various x-ray imaging schemes. For NIF, the larger target sizes and thicker shells will necessitate the use of more penetrating radiations than currently used. Higher energy x rays, neutrons and γ rays are all potentially useful.

X-ray imaging at Nova is done predominantly with systems requiring components close to the target (e.g., pinholes). In order to allow a larger stand-off distance at NIF and to work at x-ray energies that will penetrate from the core, a high energy (8-keV) x-ray imaging system based on a multi-layer coated Wolter optic is being developed. Using conventional fabrication techniques will result in an unaffordable cost for multiple imagers, so the use of replica fabrication techniques is being pursued. In this approach, a Wolter shaped mandrel is manufactured and coated with the material to be used for the mirror surface. The mandrel surface figure and roughness are critical, but costs are reduced because its exterior surface is accessible compared to the interior surface of a conventionally manufactured Wolter. The mandrel is then coated with a backing material, and the whole assembly is cooled. Differential contraction is used to break the Wolter mirror surface free from the mandrel. The mandrel can be re-used multiple times.

Neutron images of the implosion cores at Nova have been obtained by use of a thick neutron aperture and a penumbral imaging technique[11]. A new system based on this method is currently under development at Nova and should produce images with 20-micron spatial resolution. A similar system is being designed for use at NIF. The main difficulty anticipated with the NIF system is the necessity to move the aperture far from the target. The high magnification system currently used (200) would then result in an unreasonably long system, thus high resolution neutron detectors that can be used in a lower-magnification instrument are being developed. γ-ray-based systems are also under consideration, since gated instruments could be developed that give time-resolved images similar to those obtained with x-ray- based instruments. Such images are difficult to obtain with neutrons, due to the Doppler broadening discussed above.

7. Charged Particles

A variety of nuclear reactions produce multi-MeV charged particles that can escape from the implosion core and be used to make measurements complementary to those discussed above. A general-use magnetic spectrometer based on an innovative scheme using CCDs as single particle charged particle detectors is being developed at Massachusetts Institute of Technology for use at Nova and Omega and eventually at NIF[12]. Such a detector will allow measurements of fuel areal density similar to those discussed above, utilizing neutron-based techniques. In particular, tertiary protons are produced in the following three-step reaction sequence in a mixed deuterium, tritium, and ^{3}He fuel.

6)	$d + t \longrightarrow \alpha + n$	(14.05 MeV n)
7)	$n + d \longrightarrow n' + d'$	(0–12.5 MeV d)
8)	$d' + {}^3He \longrightarrow \alpha + p$	(13–31 MeV p)

Most NIF target designs utilize a cryogenic fuel shell surrounding a central gas-filled region where the ^{3}He will be localized. This central region then converges to become the “hot spot” where burn originates in the capsule. Proper formation of this hot spot is essential to high-gain ICF target designs. With the ^{3}He localized to this region, an areal density measurement based on tertiary protons gives the areal density of the hot spot, which nicely complements the areal density measurement of the total fuel obtained in the tertiary neutron technique discussed above.

The highest energy protons in the above sequence of reactions are only produced if the momenta vectors of the neutron, deuteron, and proton in reactions 7 and 8 are close to collinear. Thus, if measurements focus on high energy (>28-MeV) tertiary protons, then the areal density is determined specifically along a line from the center of the target to the detector. Multiple detectors placed at different angles could therefore be used to determine implosion symmetry. (This is also true for tertiary neutrons, but the larger, array-style detectors used for that measurement make multiple detectors less practical.) Also, energy loss as the proton leaves the target will be sensitive to the amount of material along the path of the proton, allowing another determination of asymmetries.

8. Conclusion

Many new target-measurement techniques will become possible at NIF due to the higher yields and larger targets. Damage issues and higher backgrounds also necessitate the development of new methods. However, many of the proposed schemes require technology development prior to implementation as a NIF diagnostic. A vigorous program to develop such technologies and to subsequently design and field appropriate NIF diagnostics is underway.

ACKNOWLEDGMENT

*This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract No. W-7405-ENG-48.

[1] BLUE, T.E., HARRIS, D.B., Nucl. Sci. and Eng. **77** (1981) 463.
[2] AZECHI, H., et al., Appl. Phys. Lett. **49** (1986) 555.
[3] CABLE, M.D., et al., Bull. Am. Phys. Soc. **31** (1986) 1461.
[4] NELSON, M.B., CABLE, M.D., Rev. Sci. Instr. **63** (1992) 4874.
[5] LERCHE, R.A., et al., Rev. Sci. Instr. **66** (1995) 933.

[6] CABLE, M.D., et al., Phys. Rev. Lett. **73** (1994) 2316.
[7] LEWIS, K.P., et al., Rev. Sci. Instr. **63** (1992) 1988.
[8] BRYSK, H., Plas. Phys. **15** (1973) 611.
[9] LERCHE, R.A., et al., Appl. Phys. Lett. **31** (1977) 645.
[10] CHRIEN, R.E., et al., Rev. Sci. Instr. **63** (1992) 4886.
[11] LERCHE, R.A., et al., Laser Part. Beams **9** (1992) 99.
[12] PETRASSO, R.D., et al., to be published in Phys. Rev. Lett.